# Chemical equilibration in viscous quark-gluon plasma and electromagnetic signals

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# Abstract

We investigate the chemical equilibration of the parton distributions in collisions of two heavy nuclei, assuming the partonic fluid to be ideal as well as viscous. The initial conditions are taken from HIJING calculations for Au+Au collisions at RHIC and LHC energies. It was seen that when the viscous drag is taken into account in the fluid flow, the life time of the plasma is increased by nearly a factor of 2. The temperature as well as fugacities evolve slowly than their ideal counterpart. The photon and lepton pair production was also investigated. There is a two fold increase in the photon and lepton pair numbers with viscosity on. The increase in the large  $p_T$  photons and the large invariant mass lepton pairs are due to slower rate of temperature evolution.

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#### I. INTRODUCTION

In relativistic heavy ion collisions, a strongly interacting matter called quark-gluon plasma (QGP) is expected to be formed. The two colliding nuclei can be visualized as two clouds of valence and sea partons, which pass through each other and interact [1]. The multiple parton collisions can then produce a dense plasma of quarks and gluons. After its formation, the plasma will expand, cool and become more dilute. If quantum chromodynamics admits first order deconfinement or chiral phase transition, it is likely that the system will pass through a mixed phase of quarks, gluons and hadrons, before the hadrons lose thermal contact at sufficient dilution and stream freely towards the detectors.

Several questions about the structure of the matter formed in these nuclear collisions arise. Does the initial partonic system attain kinetic equilibrium? Probably yes, as the initial parton density is large and the partons suffer many collisions in a very short time [2]. Does it attain chemical equilibrium? This will depend on the time available [3–7] to the partonic system before it convert into a mixed phase or before perturbative QCD is no longer applicable. The time available for equilibration is perhaps too short (3-5 fm/c) at the energies ( $\sqrt{s} \leq 100$  GeV) accessible to the Relativistic Heavy Ion Collider (RHIC). At the energies ( $\sqrt{s} \leq 3$  TeV/nucleon) that will be achieved at CERN Large Hadron Collider(LHC), this time could be large (more than 10 fm/c). If one consider only a longitudinal expansion of the system, the QGP formed at LHC energies could approach chemical equilibrium very closely, due to higher initial temperature predicted to be attained there. The question of chemical equilibrium has the added importance as the preequilibrium phase may influence the yield of certain quark-gluon plasma signals, such as lepton pairs, photons and hadron containing heavy quarks.

Space-time evolution of quark and gluon distributions has been investigated in the framework of parton cascade model [1], which is based on the concept of inside-outside cascade [8-10] and evolve parton distributions by Monte-Carlo simulation of a relativistic transport equation involving lowest order perturbative QCD scattering and parton fragmentations. Early calculations were done by assuming fixed  $p_T$  and virtuality cutoffs for the partonic interactions to ensure the applicability of the perturbative expansion of QCD scattering process. From numerical studies [4,11–15] three distinct phases of parton evolution can be distinguished: (1) Gluon thermalise very rapidly, reaching approximately isotropic momentum space distribution after a time of the order of 0.3 fm/c. (2) Full equilibration of gluon phase space density takes considerably longer. (3) The evolution of quark distributions lags behind that of the gluons, the relevant QCD cross sections being suppressed by a factor of 2-3. In the recently formulated self-screened parton cascade model [16] early hard scattering produces a medium which screens the longer ranged color fields associated with softer interactions. When two heavy nuclei collide at sufficiently high energy, the screening occurs at a length scale where perturbative QCD still applies. This approach yields predictions for initial conditions of the forming QGP, without the need for any ad-hoc momentum and virtuality cutoff. This calculations also indicate that the QGP likely to be formed in such collisions are far from chemical equilibrium.

Essentially same picture emerges from the study of Biro et al [3]. Their calculations were motivated to obtain a lucid understanding of the dependence of different time scales on various parameters and model assumptions and a better physical understanding of the infrared

cut off required in the parton cascade model. The parton cascade model is a complex model and it is difficult to unravel these dependence from model calculations. They assumed that after a time  $\tau_{iso}$ , the evolution of partonic system is governed by the energy-momentum conservation law. They derived a set of rate equations describing the chemical equilibration of gluons and quarks, including the medium effect on relevant transport coefficients. The initial conditions of the partonic system was obtained from HIJING calculations. Their results support the picture emerging from parton cascade model, that the plasma is essentially a gluon plasma. The gluon distributions attain near chemical equilibrium at LHC energies, and the quark distributions lag behind. At RHIC energies, the gluon as well as quark distributions are far from equilibrium. In their calculation the partonic fluid is assumed to undergo longitudinal expansion only. Effect of transverse expansion on chemical equilibration was studied in ref. [17,18]. At RHIC energies, results for pure longitudinal expansion and transverse expansion are quite similar except at large values of transverse radius. However, at LHC energies, the transverse expansion changes the scenario, the plasma initially approach the chemical equilibrium, but then is driven away from it, when the transverse velocity gradients develop. Interestingly, total parton multiplicity as well as lepton pair and photon productions are not much affected by the transverse expansion.

In all these calculations [3,17,18], the hydrodynamic evolution of the partonic system was assumed to be ideal. It is well known that dissipative effects like viscosity can affect the flow [19–21]. The system will cool slowly as viscous drag will oppose the expansion. As the chemical equilibration rate depend on the cooling rate, it will also change. In the present paper, we will explore the effect of viscosity on the evolution and equilibration of parton distributions. We will also investigate its effect on the lepton pair and photon production, typical QGP signals.

The paper is organised as follows: in section 2, we set up the basic equations for hydrodynamic and chemical evolution of the plasma, also define the viscosity coefficients. In section 3, the results will be discussed. In section 4, we study the effect of viscosity on photon and dilepton productions. Summary will be given in section 5.

## II. HYDRODYNAMIC EXPANSION AND CHEMICAL EQUILIBRATION

## A. Basic Equations

We assume that after the collision, a symmetric partonic system (QGP) is formed in the central rapidity region. We also assume that the partonic system achieves a kinetic equilibrium by time  $\tau_{iso}$ , when the momenta of partons became locally isotropic [3]. Local isotropy in momentum can be said to be established when variance in the longitudinal momentum distribution equals the variance in the transverse momentum distribution. This occurs after a proper time of about  $0.7\lambda_f$  [2],  $\lambda_f$  being the partonic mean free path. At collider energies, this time corresponds to  $\tau_{iso} \approx 0.2 - 0.3$  fm/c [3]. Beyond  $\tau_{iso}$  further expansion of the partonic system can be described by hydrodynamic equations. The approach to chemical equilibration is then governed by a set of master equation which are driven by the two body reactions  $(gg \leftrightarrow gg)$  and gluon multiplication and its inverse process, gluon fusion  $(gg \leftrightarrow ggg)$ . The hot matter continue to expand and cool due to expansion and

chemical equilibration, till the temperature falls below the critical value ( $T_c = 160 \text{ MeV}$ ), when we terminate the evolution.

We assume that the hydrodynamic expansion is purely longitudinal. As indicated in the analysis [17,18], at RHIC energies, the transverse expansion effect is minimal. It does affect the parton equilibration rate at LHC energies, the effect showing sensitive dependence on the initial condition of the plasma. For the initial condition as obtained from HIJING calculations, this effect is not large [17,18].

For boost-invariant longitudinal flow, the energy-momentum conservation equation for the partonic fluid including the viscosity, is the well known equation [19–21],

$$\frac{d\varepsilon}{d\tau} + \frac{\varepsilon + P - \frac{4/3\eta + \zeta}{\tau}}{\tau} = 0 \tag{1}$$

where  $\eta$  and  $\zeta$  are the shear and bulk viscosity coefficients. In the QGP, the bulk viscosity coefficient is zero. It is apparent that in one dimensional flow, the effect of viscosity is to reduce the pressure. One must note that, under no circumstances, the viscous drag can exceed the pressure.

Equation of state need to be specified for solving the hydrodynamic equation 1. For partially equilibrated plasma of massless particles, the equation of state can be written as [3]

$$\varepsilon = 3P = [a_2\lambda_q + b_2(\lambda_q + \lambda_{\bar{q}})]T^4 \tag{2}$$

which imply a speed of sound  $c_s = 1/\sqrt{3}$ . In Eq.2,  $a_2 = 8\pi^2/15$ ,  $b_2 = 7\pi^2N_f/40$ ,  $N_f \approx 2.5$  is the number of dynamical quark flavor.  $\lambda_i$  is the fugacity for the parton species i. Here we have defined the fugacities through the relations:

$$n_q = \lambda_q \tilde{n}_q \tag{3a}$$

$$n_q = \lambda_q \tilde{n}_q \tag{3b}$$

$$n_{\bar{q}} = \lambda_{\bar{q}} \tilde{n}_{\bar{q}} \tag{3c}$$

where  $\tilde{n}_i$  is the equilibrium density for the parton species i:

$$\tilde{n}_g = \frac{16}{\pi^2} \zeta(3) T^3 = a_1 T^3 \tag{4a}$$

$$\tilde{n}_q = \frac{9}{2\pi^2} \zeta(3) N_f T^3 = b_1 T^3 \tag{4b}$$

We further assume that  $\lambda_q = \lambda_{\bar{q}}$ . Denoting the derivative with respect to  $\tau$  by an overdot, eq.1 can be rewritten as,

$$\frac{\dot{\lambda}_g + b(\dot{\lambda}_q + \dot{\lambda}_{\bar{q}})}{\lambda_g + b(\lambda_g + \lambda_{\bar{q}})} + 4\frac{\dot{T}}{T} + \frac{4}{3\tau} - \frac{4}{3\tau} \frac{\eta}{\tau^2} \frac{1}{[a_2\lambda_g + b_2(\lambda_g + \lambda_{\bar{q}})]T^4} = 0 \tag{5}$$

where  $b = b_2/a_2 = 21N_f/64$ . If the partonic fluid is considered to be ideal fluid,  $\eta = 0$  and the above equation can be integrated to obtain,

$$[\lambda_q + b(\lambda_q + \lambda_{\bar{q}})]^{3/4} T^3 \tau = const. \tag{6}$$

For a fully equilibrated plasma,  $(\lambda_g = \lambda_q = \lambda_{\bar{q}} = 1)$ , and we obtain the Bjorken scaling law  $T^3\tau = const$ . For viscous fluid, eq.5 can not be integrated and has to be evaluated numerically.

The master equation for the dominant reaction channels  $gg \leftrightarrow ggg$  and  $gg \leftrightarrow q\bar{q}$  for chemical equilibration are,

$$\partial_{\mu}(n_g u^{\mu}) = n_g (R_{2\to 3} - R_{3\to 2}) - (n_g R_{g\to q} - n_q R_{q\to g}) \tag{7}$$

$$\partial_{\mu}(n_q u^{\mu}) = \partial_{\mu}(n_{\bar{q}} u^{\mu}) = (n_g R_{g \to q} - n_q R_{q \to g}) \tag{8}$$

in an obvious notation. Using Juttner distribution for the phase space distribution for the partons, the rates can be factorized as [3],

$$n_g(R_{2\to 3} - R_{3\to 2}) = \frac{1}{2}\sigma_3 n_g^2 (1 - \frac{n_g}{\tilde{n}_g})$$
 (9a)

$$n_g R_{g \to q} - n_q R_{q \to g} = \frac{1}{2} \sigma_2 n_g^2 \left(1 - \frac{n_q n_{\bar{q}} \tilde{n}_g^2}{\tilde{n}_g \tilde{n}_{\bar{q}} n_q^2}\right)$$
 (9b)

where  $\sigma_3$  and  $\sigma_2$  are thermally averaged, velocity weighted cross sections,

$$\sigma_3 = \langle \sigma(gg \to ggg)v \rangle$$
 (10a)

$$\sigma_2 = \langle \sigma(gg \to q\bar{q})v \rangle,$$
 (10b)

Defining density weighted reaction rates;  $R_3 = \frac{1}{2}\sigma_3 n_g$  and  $R_2 = \frac{1}{2}\sigma_2 n_g$ , eq.8 can be written as,

$$\frac{\dot{\lambda}_g}{\lambda_g} + 3\frac{\dot{T}}{T} + \frac{1}{\tau} = R_3(1 - \lambda_g) - 2R_2(1 - \frac{\lambda_q \lambda_{\bar{q}}}{\lambda_g^2}) \tag{11}$$

$$\frac{\dot{\lambda}_q}{\lambda_q} + 3\frac{\dot{T}}{T} + \frac{1}{\tau} = R_2 \frac{a_1}{b_1} \left(\frac{\lambda_g}{\lambda_q} - \frac{\lambda_{\bar{q}}}{\lambda_g}\right) \tag{12}$$

Biro et al [3] have evaluated the reaction rates  $R_2$  and  $R_3$ , taking into account the color Debye screening and the Landau-Pomeranchuk-Migdal effect suppressing the induced gluon radiation. The results are,

$$R_2 \approx 0.24 N_f \alpha_s^2 \lambda_g T \ln(1.65/\alpha_s \lambda_g) \tag{13}$$

$$R_3 = 2.1\alpha_s^2 T (2\lambda_g - \lambda_g^2)^{1/2} \tag{14}$$

The coupled Eqs(5,11,12) determine the evolution of  $T(\tau)$ ,  $\lambda_g(\tau)$  and  $\lambda_q(\tau)$  towards the chemical equilibrium and are solved numerically. It may be noted that the rate equations (11,12) may give negative growth rate for the fugacities, in case of very slow cooling. For viscous fluid, viscosity being temperature dependent, the cooling is slowed down, and such a situation may arise at early times when the temperature of the partonic system is very large. However, physics of the problem require that fugacities can grow only. Thus, while solving eqs(11,12), we impose the additional constraint that,

$$\dot{\lambda}_{q,q} \ge 0 \tag{15}$$

#### B. Viscosity coefficient

Several results for viscosity coefficients for QGP system is available [19,20,22–24]. Thoma [24] has calculated the shear viscosity coefficient of the QGP, in the relaxation time approximation. Screening effects were taken into account by using an effective perturbation theory developed for the finite temperature QCD, in the weak coupling limit [25]. His results agree well with the variational calculation of Baym et al [23], and will be used in the present calculation.

$$\eta_q = 0.82 \frac{T^3}{\alpha_x^2 \ln(1/\alpha_s)}$$
(16a)
$$\eta_g = 0.20 \frac{T^3}{\alpha_x^2 \ln(1/\alpha_s)}$$
(16b)

$$\eta_g = 0.20 \frac{T^3}{\alpha_x^2 \ln(1/\alpha_s)} \tag{16b}$$

For plasma, away from equilibrium, the shear viscosity coefficient for QGP then can be written as,

$$\eta = \lambda_g \eta_g + \lambda_g \eta_g \tag{17}$$

with  $\eta_{q,q}$  given in eq.16.

We have assumed that the dominant reactions towards the chemical equilibrium are the  $gg \leftrightarrow ggg$  and  $gg \leftrightarrow q\bar{q}$  reactions. The reaction rates for these processes (eq.13,14) can be used in the kinetic approximation to obtain the shear viscosity coefficients. In the kinetic approximation,

$$\eta \approx \frac{4}{15} n_i < p_i > \lambda_i \tag{18}$$

where  $n_i$  and  $\langle p_i \rangle$  are the density and average momentum of the particles of type i and  $\lambda_i$  is its mean free path. Using  $\langle p \rangle = 3.2T$  the viscosity coefficient can be written as,

$$\eta = \frac{12.8}{30} \frac{a_1 T^3}{\frac{R_3}{T} + \frac{R_2}{T}} \tag{19}$$

In the following calculations we will use both the viscosity coefficients eq.17 and eq.19, and will be referred as vicosity coefficient I and II respectively.

#### C. Results for RHIC and LHC energies

The initial conditions for the hydrodynamic evolution are listed in table (1) [3]. They are the results of HIJING model calculation, which is a QCD motivated phenomenological model, as only initial direct parton scatterings are taken into account. Thus there are some uncertainties in these parameters. However, they suffice our purpose of demonstrating the effect of viscosity on parton equilibration process.

In fig.1a,b and c, we have shown the evolution of the temperature, the gluon fugacity and the quark fugacity at RHIC energy. The solid line corresponds to the ideal flow, i.e. no viscous drag, the dashed and the long dashed lines are with viscous drag, corresponding to shear viscosity coefficients I and II As expected, with viscosity, temperature of the partonic system evolve more slowly. Viscosity oppose the expansion, consequently, cooling is slowed down. The lifetime of the QGP phase is considerably increased in presence of viscosity (by nearly a factor of 2). It is apparent that this will have considerable effect on signals of QGP such as dileptons and photons. We also note that temperature evolution do not differ much with different prescriptions for  $\eta$ . Life time being changed by less than 2%.

The evolution of gluon fugacity is much more interesting. With viscosity, gluon fugacity also evolves more slowly. Viscosity impedes the chemical equilibration process. We find that upto 2 fm,  $\lambda_g$  do not change, it then increases slowly, much more slowly than for the ideal fluid. This is contrary to the expectation from ideal fluid flow (eq.6) that if the temperature evolve slowly, fugacities will increase at a faster rate. Indeed for viscous fluid flow, eq.6 is no longer valid. The behavior of  $\lambda_g$  can be understood by recasting eq.4 as,

$$\frac{\dot{\lambda}_g}{\lambda_g} = -3\frac{\dot{T}}{T} - \frac{1}{\tau} + R_3(1 - \lambda_g) - 2R_2(1 - \frac{\lambda_q \lambda_{\bar{q}}}{\lambda_q^2}) \tag{20}$$

Then as the temperature decreases more slowly, rhs of eq.20 will decrease as a result of which, fugacity will also evolve slowly. Thus viscosity, affect both the temperature and fugacity evolution, requiring them to evolve more slowly than their *ideal* counterpart. We also note that in the viscous partonic system, the gluon fugacity could not attain the value reached in the ideal case, by the time the system is cooled to  $T_c$ , even though the life time is considerably increased.

In fig.1c, the quark fugacity is shown. They show a similar behavior as gluon fugacity. As with gluon fugacities, quark fugacities also evolve much more slowly if the viscosity is turned on, for the same reasons as described above. By the time  $T_c$  is reached, they are far behind chemical equilibrium. Here also, the fugacities do not attain the value reached in the ideal case at  $T_c$ .

The results for evolution of temperature and fugacities at LHC energies are nearly the same, as shown in fig.2a,b and c. Here also, with viscosity, plasma cools slowly than the ideal fluid, life time of the plasma increasing by a factor of 2. The gluon and quark fugacities also evolve slowly. In contrast to RHIC energy, gluon and quark fugacities attain larger values at  $T_c$ . This is due to their comparatively large initial values. Thus our initial conjecture that chemical equilibrium is attained at LHC energies but not at RHIC is substantiated. However, we note that even at LHC energies, the plasma is not fully equilibrated,  $\lambda_g \approx 0.7$  and  $\lambda_q \approx .5$ , and are quite far from equilibrium.

#### III. THERMAL PHOTONS AND LEPTON PAIRS

## A. Photon spectra

Thermal photons and lepton pairs are primary probes of quark-gluon plasma. Being weakly interacting, they carry the information of the early phase of the hot fireball created in the collision. Thermal photons from QGP has their origin in the Compton  $(qg \to q\gamma)$  and annihilation processes  $(q\bar{q} \to g\gamma)$  processes. For plasma away from equilibrium, their rates have been calculated [26]

$$E\frac{dN}{d^{3}pd^{4}x} = \frac{2\alpha\alpha_{s}}{\pi^{4}}\lambda_{q}\lambda_{g}T^{2}e_{q}^{2}exp(-E/T)\left[\ln(\frac{4ET}{k_{c}^{2}}) + 1/2 - C\right]$$
(21)

and the rate for annihilation process is,

$$E\frac{dN}{d^3pd^4x} = \frac{2\alpha\alpha_s}{\pi^4}\lambda_q\lambda_{\bar{q}}T^2e_q^2exp(-E/T)\left[\ln(\frac{4ET}{k_c^2}) - 1 - C\right]$$
(22)

Here C=0.577721,  $e_q$  is the electric charge of the quark and the parameter  $k_c$  is related to thermal mass of the quark in the medium,

$$k_c^2 = \frac{1}{3}g^2\kappa^2 T^2 = 2m_q^2 \tag{23}$$

with [3]

$$m_q^2 = \left(\lambda_g + \frac{1}{2}\lambda_q\right) \frac{4\pi}{9} \alpha_s T^2 \tag{24}$$

In fig.4 and 5, we have shown the photon spectra, as obtained presently, with and without viscous drag at RHIC and LHC energies. It can be seen that photon production is increased by a factor of 2 with viscosity turned on. With viscosity turned on, life time of the plasma is increased nearly by a factor of 2 and it is natural that photon yield will also be increased. However, we have checked that the increase in photon yield beyond  $p_T \geq 2$  GeV is not due to increased life time of the plasma, rather, it is due to the slower cooling and lower equilibration rate of the of the viscous plasma. The increase in low  $p_T$  yield can be attributed to the longer lifetime of the plasma. Also we note that, the photon yield do not depend much on the two version of viscosity coefficients used. The yield is marginally increased at low  $p_T$  with viscosity coefficient II, than with viscosity coefficient I, and essentially due to the larger lifetime of the plasma.

#### B. Lepton pair spectra

The transverse mass distribution of lepton pairs from nonequilibrium plasma can be written as [26],

$$\frac{dN}{dM^2 d^2 M_T dy} = \frac{\alpha^2}{4\pi^3} e_q^2 R_T^2 \int \lambda_q \lambda_{\bar{q}} \tau d\tau K_0(\frac{M_T}{T})$$
 (25)

In fig.5 and 6, we have shown the invariant mass distribution of lepton pairs at RHIC and LHC energies. As before, we have shown the results with and without viscous drag. Here again, we find that the lepton pair yield in increased by a factor of 2, when the viscosity is turned on. As found with the photon spectra, here also, large mass ( $M \geq 2$  GeV) yield of of lepton pairs are essentially due to slower cooling and equilibration rate of the viscous plasma, rather than its increased lifetime. The increase in the low mass yield can be said to be due to the increased lifetime of the plasma. As with photon spectra, the lepton pair yield with two different viscosity coefficients do not differ much.

The analysis clearly indicate that photon and dilepton yield in QGP are greatly affected if dissipative effects like viscosity is taken into account. Large invariant mass lepton pairs

and also large  $p_T$  photons yields are increased by a factor of two, from their ideal counterpart. This increase is essentially due to lower cooling and equilibration rate. The low  $p_T$  photons and the low invariant mass dileptons are also increased, but mainly due to increased life time of the viscous plasma.

#### IV. SUMMARY

We have investigated the effect of viscosity on chemical equilibration of parton distribution in relativistic heavy ion collisions. We assumed that after a time  $\tau_{iso}$ , the partonic system achieved kinetic equilibrium. Beyond  $\tau_{iso}$  expansion (which we assumed to be boost-invariant longitudinal only) is governed by the hydrodynamic equations. The approach to the chemical equilibration process is then governed by a set of master equations which are driven by the two body reactions  $gg \leftrightarrow q\bar{q}$  and  $gg \leftrightarrow ggg$ . The partonic matter continue to expand and cool due to expansion and chemical equilibration, till the critical temperature ( $T_c$ =160 MeV) is reached. Initial condition of the plasma was taken from HIJING calculations. It was seen that with viscosity turned on, the temperature of the partonic system evolve slowly, in comparison to the ideal system. This is expected, as viscosity impedes the expansion, making the cooling a slower process. Interestingly, we find that the chemical equilibration rate is also slowed down in presence of viscous drag. This is in contrast to the ideal partonic system behavior, where, lower cooling rate implies a faster equilibration. We thus find that even though the life time of the plasma is increased by nearly a factor of 2, the gluon or quark fugacity could not attain the value that is reached in case of ideal flow.

The effect of lower cooling and equilibration rate on photon and lepton pair production was also studied. It was seen that with viscosity, the photon as well as lepton pair yield increased by nearly a factor of 2, both at RHIC and LHC energies. The increase in large  $p_T$  photons or large invariant mass dileptons are essentially due to the lower cooling rate, rather than the large life time of the viscous plasma. The increase in the low  $p_T$  photon or low invariant mass dileptons can be attributed to the to the longer life of the plasma.

To conclude, viscosity can have a significant effect on parton equilibration process, by slowing down the cooling rate and the chemical equilibration process. Its effect is also manifest in the pre-equilibrium photon and dilepton production, raising their yield by nearly a factor of 2.

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 ${\it TABLES}$  Initial conditions characterising the parton plasma at the onset of hydrodynamic evolution

	RHIC	LHC
$\overline{ au_{iso}(\mathrm{fm/c})}$	0.31	0.23
$T_0({ m GeV})$	0.57	0.83
$\lambda_q^0$	0.09	0.14
$\lambda_q^{0}$	0.02	0.03

# **FIGURES**

- FIG. 1. Evolution of temperature, gluon fugacity and quark fugacity with proper time at RHIC.
- FIG. 2. Evolution of temperature, gluon fugacity and quark fugacity with proper time at LHC.
  - FIG. 3. Transverse momentum distribution of photons at RHIC
  - FIG. 4. Transverse momentum distribution of photons at LHC
  - FIG. 5. Invariant mass distributions of lepton pairs at RHIC.
  - FIG. 6. Invariant mass distributions of lepton pairs at LHC.

